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MENTAL ROTATION AND TEMPORAL CONTINGENCIES

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A task that requires subjects to determine whether two forms of the same shape, but in different orientations, are mirror images or identical except for orientation is called a *handedness recognition task*. Subjects' reaction times (RT) on this task are consistently related to the angular disparity (termed α) between the two presented forms. This pattern of data has been interpreted to indicate that subjects solve the task by imagining that one of the forms rotates into the orientation of the other (termed *mental rotation*). The speed with which one imagines one of the forms rotating has been widely considered a fixed capability of the individual, and thus immune to the effect of contingencies. We present an experiment that assesses the effects of temporal contingencies in a handedness recognition task on the slope of the function RT = $f(\alpha)$. The data indicate that the slope of this function can come under the control of temporal contingencies.

Key words: private event, temporal contingencies, mental rotation, reaction time, humans

A task that requires subjects to determine whether two forms of the same shape, but in different orientations, are mirror images or identical except for orientation is called a *handedness recognition task* (see Figure 1). A critical dependent variable in a handedness recognition task is the subject's response time (RT). Subjects' RTs from this task are consistently related to the angular disparity (termed α) between the two presented forms (Corballis, 1988; Shepard & Cooper, 1982; Shepard & Metzler, 1971). Specifically, RTs are a linear monotonically increasing function of α (see Figure 1). This pattern of response is similar to the pattern one would expect if the subject physically rotated one of the forms into the orientation of the other. The original authors have therefore interpreted this pattern to indicate that subjects use a strategy that involves imagining one of the forms to rotate into the orientation of the other (Shepard & Metzler, 1971). When the two forms are imagined in the same orientation, subjects match the two patterns and make their response. This strategy has been termed *mental rotation*.

The mental rotation strategy can be interpreted as an instance of what Skinner (1953) called *operant seeing*. For example, Skinner (1953, p. 273) describes how imagining a sectioned painted cube (similar to a Rubik's cube) may help in determining the number of sections with single, double, or triple painted sides: "one may *see* the larger cube, *separate* the smaller cubes covertly, *see* their faces, *count* them subvocally, and so on." Implied by such an interpretation is a relation between the covert behavioral sequences and measures of overt behavior. One should be able to predict, for example, that the time it takes to respond is an increasing function of the number of cubes one needs to count. Similarly, for the handedness recognition task, the slope of the function RT = $f(\alpha)$ has been interpreted as a marker indicating the speed of mental rotation. Using this function as a marker for a covert behavioral sequence, we will assess whether some aspect of this sequence can come under the control of temporal contingencies.

Reaction times have been brought under control of temporal contingencies for tasks other than handedness recognition tasks (Baron & Menich, 1985; Baron, Menich, & Perone, 1983; Blough, 1992). For example, Baron et al. (1983) reinforced progressively faster responses in a match-to-sample task in human subjects. Subjects consistently responded more quickly in the condition in which the temporal contingency was enforced. In addition, when the temporal contingency was removed, subjects continued to respond at speeds comparable to those in the quickest treatment conditions. These results indicate that temporal contingencies can con-

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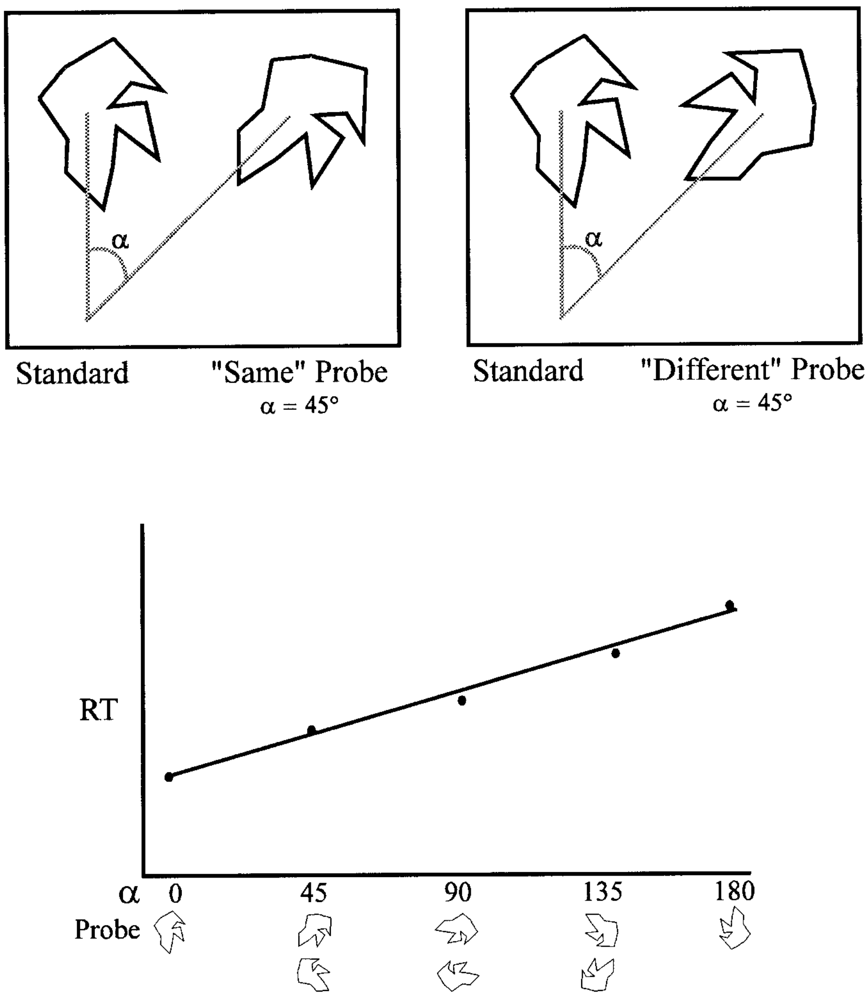


Fig. 1. Examples of trials in the handedness recognition task. The top left panel shows a trial in which the two polygons should be classified as the same. The top right panel shows a trial in which the two polygons should be classified as different. The plot on the bottom shows an idealized function relating RT and angular disparity for a typical subject in a handedness recognition task.

trol RTs in some tasks. Furthermore, these contingencies generate a behavior pattern that persists past the point at which contingencies are removed.

Although RTs have been brought under the control of temporal contingencies, some would predict that the slope of the function RT = $f(\alpha)$ is impervious to such contingencies. Traditionally, the slope of this function is taken to indicate the speed of the imagined rotation. Metzler and Shepard (1974) state that "the subject . . . can perform this analog process [mental rotation] at no faster than some limiting rate" (quoted from Shepard & Cooper, 1982, p. 43). This *limiting rate criterion* has been widely interpreted in the perception literature to indicate that the speed of the imagined rotation is a fixed capability of the individual. Metzler and Shepard thought that this limiting rate corresponded to about 16.67 ms per degree. Recently, however, that limiting rate has been shown to approximate 1 ms per degree (for a discussion, see Cohen & Kubovy, 1993). Speeds equal to or faster than 1 ms per degree are generally found in tasks other than handedness recognition tasks, such as letter identification tasks (i.e., the subject must name a misoriented letter;

Corballis & Nagourney, 1978; Corballis, Zbrodoff, Shetzler, & Butler, 1978). The shallow slopes in these tasks have been attributed to the subject quickly searching the stimulus for an identifying landmark. The qualitative difference between large and small slopes has not been much debated in the literature (Cohen & Kubovy, 1993).

There is, however, also justification for the prediction that the slope of the function RT $= f(\alpha)$ can come under the control of temporal contingencies. The limiting rate criterion was deduced from experiments in which instructions were used to induce subjects to respond quickly (e.g., "please respond as quickly and accurately as possible"). These instructed contingencies may not exert as much control as other, more immediate, contingencies (Baron & Menich, 1985; Baron et al., 1983). Thus, the exclusive use of instructions may have led to the possibly erroneous conclusion that the speed of the imagined rotation is a fixed capability of the individual.

Recently, Cohen and Kubovy (1993) have shown that the slope of the function RT = $f(\alpha)$ could be influenced by temporal contingencies. They presented a handedness recognition task to two groups of subjects. One group received a temporal contingency in the form of a posttrial beep if the subject did not respond faster than a preset deadline. The second group did not receive the temporal contingency. The results showed that the group who received the temporal contingency accurately performed the task without showing a pattern of response consistent with a mental rotation strategy (i.e., RT was unrelated to α). The second group showed a pattern of responses consistent with a mental rotation strategy (i.e., RT was a linear monotonically increasing function of α). This experiment demonstrated that the temporal contingency influenced the subjects' performance in the handedness recognition task.

Although Cohen and Kubovy (1993) established that temporal contingencies influence subjects' slopes relating RT = $f(\alpha)$, their experimental design could not address many important issues. First, the effects present in a group design may not accurately reflect the behavior of individual subjects. To illustrate, the distributions of slopes from the two groups overlapped in Cohen and Kubovy's study. Because no stable baseline measure was taken, one cannot determine whether the temporal contingency reduced all subjects' slopes (though not to zero) relative to their baseline, or alternatively, greatly reduced steep slopes while having little or no effect on the shallower slopes. In addition, Cohen and Kubovy had each subject participate in the handedness recognition task only once. Therefore, they were unable to assess the effects of learning. For instance, are subjects performing optimally during a single exposure to the handedness recognition task, and if not, does that interact with the effect of temporal contingencies? Furthermore, is the full effect of the temporal contingency on subjects' slopes apparent in a single exposure to the handedness recognition task? We present below a single-subject experiment that begins to explore the influence of temporal contingencies on the slope relating RT = $f(\alpha)$ in detail.

METHOD

Subjects

Two males (Subject 1, age 28, and Subject 2, age 22) and 1 female (Subject 3, age 20) attending the University of North Carolina at Wilmington were paid for their participation in the experiment.

Stimuli and Apparatus

Two new 14-sided polygons were randomly generated for each session. New stimuli were generated for each session to eliminate the possibility that subjects could learn the characteristics of the stimuli in each presented orientation. The stimuli were generated by the random selection of 14 points within an imaginary 300 × 300 pixel matrix. The lines between the points were then connected clockwise around the center. The size of each polygon was standardized by selecting the distance between the two furthest points and then scaling the polygon so that distance equals 4.2° visual angle. If any particular side of a polygon was smaller than 0.5° visual angle, that polygon was filtered out and a new polygon was generated. The mirror-reversed version of the standard polygon was then constructed. The standard and mirror-reversed polygons were generated at the beginning of each session.

The stimuli were constructed on a Digital

DeCpc LPv 433dx personal computer and were presented on an Digital 13-in. monitor. Throughout the experiment the subject sat in front of the computer in a small dark room except when instructions were given and between sessions. The subject was seated approximately (20 in.) 51 cm from the screen, and each polygon subtended 4.2° visual angle.

Procedure

Each subject performed multiple sessions of a handedness discrimination task over a 3-month period. The handedness discrimination task consisted of two polygons, termed the *standard* and the *probe* (described above), presented side by side. Each trial consisted of a standard polygon on the left side of the screen and a probe polygon on the right side of the screen. The standard polygon was always one of the two polygons generated at the beginning of the session, and was always presented at the same orientation. The probe polygon was either a misoriented version of the standard polygon or a misoriented mirror-reversed version of the standard polygon. The standard and the probe polygons were separated by 4.2° visual angle. The probe polygons were generated by rotating the standard polygon, or the mirror-reversed version of the standard polygon, 360° around its geometric center in 2° steps. Thus for each of the two standard polygons, 360 probes were created (180 misoriented versions of the standard and 180 misoriented mirror-reversed versions of the standard). The subject's task was to determine whether the two stimuli could be rotated, in the two dimensional plane of the computer screen, into congruence. If the two polygons could be rotated into congruence (termed *same* trials), the subject was to respond by pressing the D key on the keyboard. If the two polygons could not be rotated into congruence (termed *different* trials), the subject was to respond by pressing the K key on the keyboard. Reaction times were recorded in milliseconds from the presentation of the trial to the subject's response.

An experimental session consisted of 720 trials, for which each trial consisted of a different standard-probe combination. After each trial, accuracy feedback (i.e., CORRECT or INCORRECT) was visually presented for 800 ms. There was a 500-ms blank screen before the beginning of the next trial. The orders of the trials were randomized before each session, with a constraint that the two standard polygons alternated from trial to trial. This constraint was implemented so that the position of the probe on the previous trial could not influence the subject's strategy on the current trial. Before each experimental session, 40 practice trials were presented. The format of the practice trials was identical to that of the experimental trials, with the exception that the probe polygons were rotated around their geometric center in 36° steps.

There was a self-timed break between the practice and experimental trials. There were additional self-timed breaks every 200 trials. Trials on which errors were made were randomly re-presented throughout each session. Subjects were tested individually for 1-hr per day, 3 days per week. On average, two experimental sessions were completed during each 1-hr meeting.

There were two experimental conditions: a no-RT pressure condition and an RT pressure condition. In the no-RT pressure condition, subjects were instructed to respond as quickly as possible. No other contingencies were implemented. In the RT pressure condition, both temporal and instructional contingencies were implemented to quicken subjects' responses. All subjects first participated in the no-RT pressure condition until the slopes of the RT function reached stability. A moving window of six experimental sessions was analyzed to determine stability. The stability criterion was implemented on the slope of the function RT = $f(\alpha)$ for the same trials in each experimental session. This function was computed using a least absolute values procedure to reduce the effects of outliers. To determine stability, the mean slope from the first three sessions was subtracted from mean slope of the last three sessions (of the six-session moving window), and this difference was divided by the mean slope for all six of the most recent sessions [i.e., $(M_{1\text{-}3} - M_{4\text{-}6})/M_{1\text{-}6}$; Perone, 1991]. The resulting percentage must have been equal to or less than 10% for the subject's performance to be considered stable. After the slope for a given subject reached stability in the no-RT pressure condition, the RT pressure condition was implemented. For the 2 subjects who reached stability in the RT pressure condition, a second no-RT pressure condition was presented. Thus, with the exception of Subject 3, who left the study during the RT pressure condition, the subjects were again allowed to respond at their own pace. The second no-RT pressure condition for Subjects 1 and 2 was terminated due to the end of the semester.

No-RT pressure condition. On the 1st day, each subject received the following verbal instructions on how to perform the handedness discrimination task in the no-RT pressure condition:

> In this experiment you will be presented two polygons simultaneously. Your task is to decide, as quickly as possible, whether the two polygons are the same or different. The two polygons are considered the same if one of the two can be rotated in the two-dimensional plane so that it matches the other polygon. The polygons are considered to be different if they cannot be rotated into congruence.
>
> There will be two sets of polygons for each session. The polygon on the left side of each set is called the standard. This polygon will stay in the same orientation in each set for each presentation. The polygon on the right side of each set of polygons is called the probe. It will vary in orientation and shape. Your task is to decide if the polygons are the same or different.
>
> When you begin, the computer will indicate which key to press if the polygons are the same and which key to press if the polygons are different. Once you have made your decision, press the appropriate key as quickly as possible. Speed is important, but accuracy is essential. Do you have any questions?

RT pressure condition. Once the slopes were stable in the no-RT pressure condition, the subject began performing the handedness discrimination task under the RT pressure condition. At the beginning of the RT pressure condition, the subject received the same set of instructions as in the no-RT pressure condition, with the following instruction added at the end of the second paragraph: "If you take too long to respond, you will hear a loud beep after you make your decision. This indicates that you have responded too slowly and that you should respond faster on the next trial."

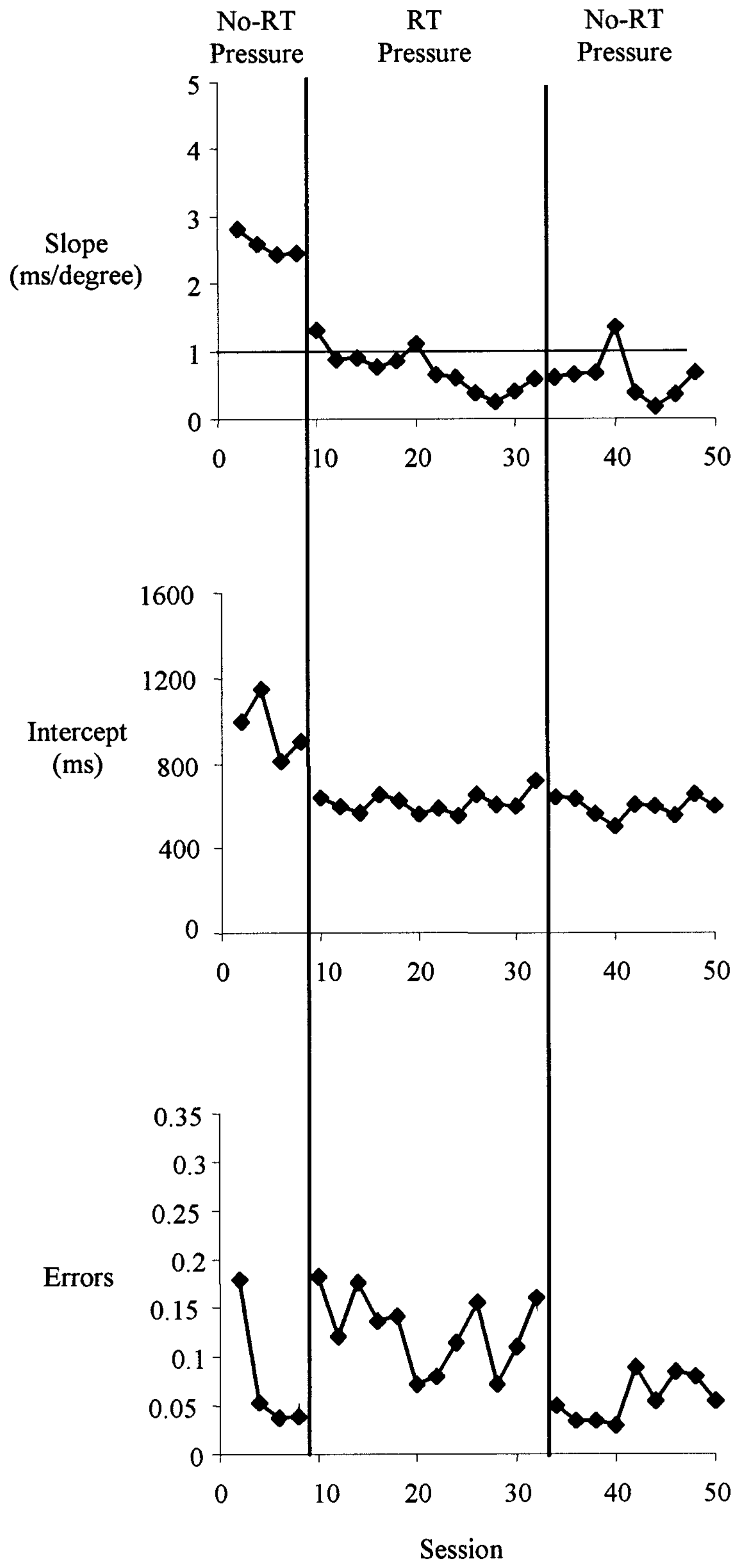
The handedness discrimination task in the RT pressure condition was identical to that of the no-RT pressure condition with the addition of a temporal contingency. The temporal contingency consisted of a loud beep after a slow trial as compared to previous trials. The contingency was identical to Cohen and Kubovy's (1993) RT pressure method of Experiment 3 and consisted of setting a temporal deadline. If the subject's RT was greater than the temporal deadline, the computer sounded a loud beep after the subject's response. The temporal deadline was based on a percentile schedule (Galbicka & Platt, 1989) using the RT distribution of a moving window of the 40 preceding trials. The temporal deadline equaled the 85th percentile of the RTs in the moving window. If the previous temporal deadline was less than the present temporal deadline, the previous temporal deadline was used. To prevent high error rates the following condition was imposed: If the overall error rate in all the preceding trials of a session was greater than 15%, and the 85th percentile of the RTs in the current window was lower than the 85th percentile of the preceding window, the computer then based the deadline on the preceding window.

RESULTS

In the first no-RT condition, stability was reached by Subject 1 in seven sessions, Subject 2 in 22 sessions, and Subject 3 in 16 sessions (see Figures 2, 3, and 4). All subjects' slopes stabilized in the first no-RT pressure condition above the 1 ms per degree limiting rate criterion. Slopes above 1 ms per degree have sometimes been interpreted as indicating that the subjects were using a mental rotation strategy. After RT pressure was implemented, all subjects' slopes were at or below the 1 ms per degree threshold. Thus when temporal contingencies were imposed, by that criterion our subjects' strategy would *not* be classified as mental rotation.

Two subjects reached stability in the RT pressure condition: Subject 1 in 24 sessions and Subject 2 in 16 sessions. For these subjects, a second no-RT pressure condition was presented. Interestingly, when the no-RT pressure condition was reimplemented, the subjects' slopes remained below the 1 ms per degree threshold. Throughout the experiment, all subjects' intercepts tended to decrease.

For illustrative purposes, Figure 5 presents


No-RT Pressure
RT Pressure
No-RT Pressure
Slope (ms/degree)
5
4
3
2
1
0
0
10
20
30
40
50
Intercept (ms)
1600
1200
800
400
0
0
10
20
30
40
50
Errors
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
Session

the data in a more traditional manner. The mean RT data for all sessions are plotted in 20° intervals for each of the three conditions. There was a strong relationship between RT and α in the first no-RT pressure condition. However, this relationship diminished when the temporal contingency was implemented and did not return when the contingency was removed.

Examination of the subjects' error rates shows an interesting pattern. Subjects 1 and 3 had generally low error rates throughout the initial no-RT pressure condition (around 5%). Error rates increased when the temporal contingency was implemented (Subject 1 about 12%; Subject 3 about 30%). It is important to note that when the temporal contingency was removed for Subject 1, his error rates decreased to the levels of the first no-RT pressure condition, and his slopes remained below the 1 ms per degree threshold. The no-RT pressure condition was not re-presented to Subject 3 because her slopes did not stabilize in the RT pressure condition before the experiment was terminated by the end of the semester. The error rates of Subject 2 were not systematically related to condition, in that they tended to increase throughout the experiment.

DISCUSSION

This single-subject study demonstrates that the slopes of the function RT = $f(\alpha)$ are not a fixed capability of the individual. Whereas the experiments performed by Cohen and Kubovy (1993) demonstrated that group means could be influenced by temporal contingencies, the present study demonstrates the effect in individual subjects. How one interprets this finding is dependent upon whether one accepts that slopes at or below 1 ms per degree are (a) a qualitatively different response class from those above 1 ms per degree or (b) only quantitatively different from those above 1 ms per degree.

If one accepts that slopes at or below 1 ms per degree indicate a qualitatively different response class from those above 1 ms per degree, then the data indicate that strategies other than mental rotation can efficiently determine the handedness of a stimulus. The hypothesis that mental rotation is necessary because no other mechanisms developed to recognize misoriented objects is popular in the object recognition literature (e.g., Corballis, 1988; Takano, 1989; Tarr, 1995; Ullman, 1989). Our data refute this assumption by revealing that subjects can recognize misoriented objects without performing mental rotation. Our subjects were capable of using other, more efficient, strategies to determine the parity of an object.

If one accepts that slopes at or below 1 ms per degree are only quantitatively different from those above 1 ms per degree, then the data indicate that the speed of mental rotation is not a fixed capability of the individual. The finding that the speed with which one performs a mental rotation can come under the control of temporal contingencies tempers Metzler and Shepard's (1974) claim that "the subject . . . can perform this analog process [mental rotation] at no faster than some limiting rate" (quoted from Shepard & Cooper, 1982, p. 43).[1] This claim was made based on data from experiments in which instructed contingencies were used exclusively. The effectiveness of the temporal contingency at

[1] One can argue that the baseline behavior of our subjects was above this limiting rate, and that their behavior during the temporal contingency represents each subject's limiting rate. This interpretation is not parsimonious for two reasons. First, Shepard and Metzler made explicit that the subject's limiting rate was apparent from the subject's baseline behavior. Second, when exposed to the temporal contingency, our subjects' slopes were too shallow for the term *limiting rate* to be applied meaningfully.

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Fig. 2. Slope, intercept, and error data for Subject 1. Because subjects' responses to different trials tend to be noisy and the angular disparity of mirror-reversed polygons is equivocal, all data presented are subjects' responses to the same trials in the handedness recognition task (Cohen & Kubovy, 1993). The top two graphs contain the average slope (in milliseconds per degree) and intercept (in milliseconds) for the function RT = $f(\alpha)$ for every two experimental sessions. This function was calculated using a least absolute values procedure to reduce the effects of outliers. The bottom graph contains the error rate for those experimental sessions. Vertical lines separate no-RT pressure from RT pressure conditions.

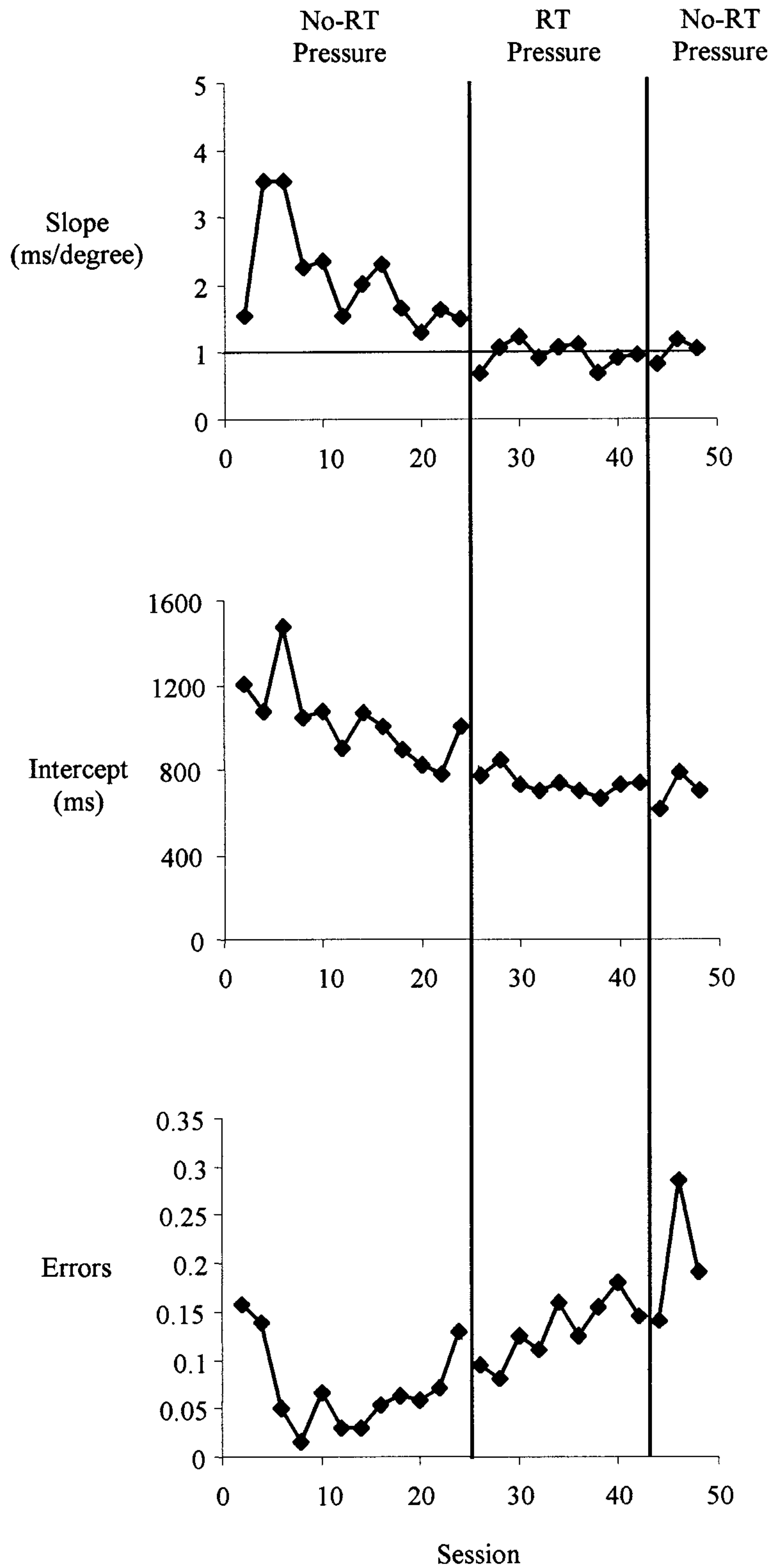


Fig. 3. Slope, intercept, and error data for Subject 2. See the caption of Figure 2 for details.

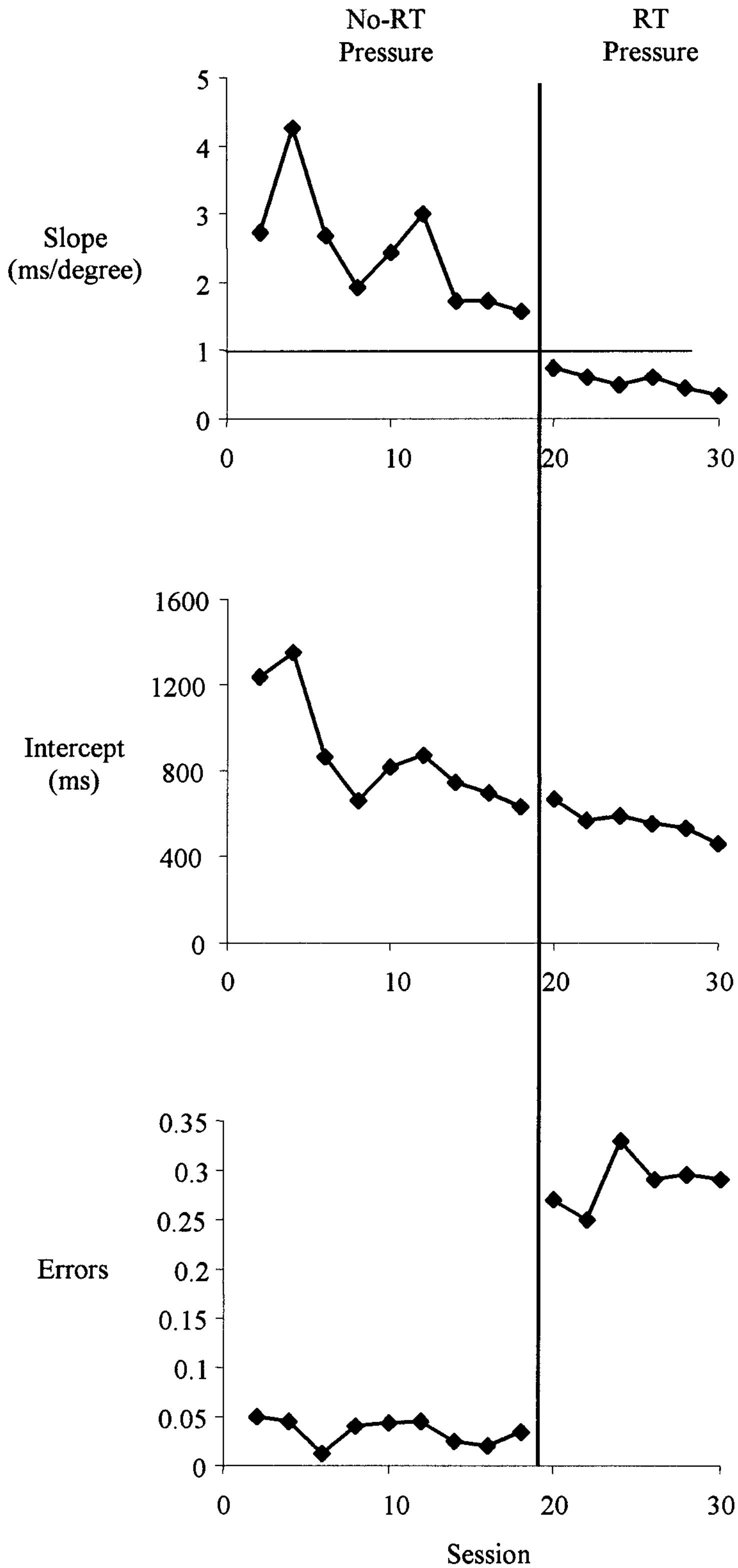
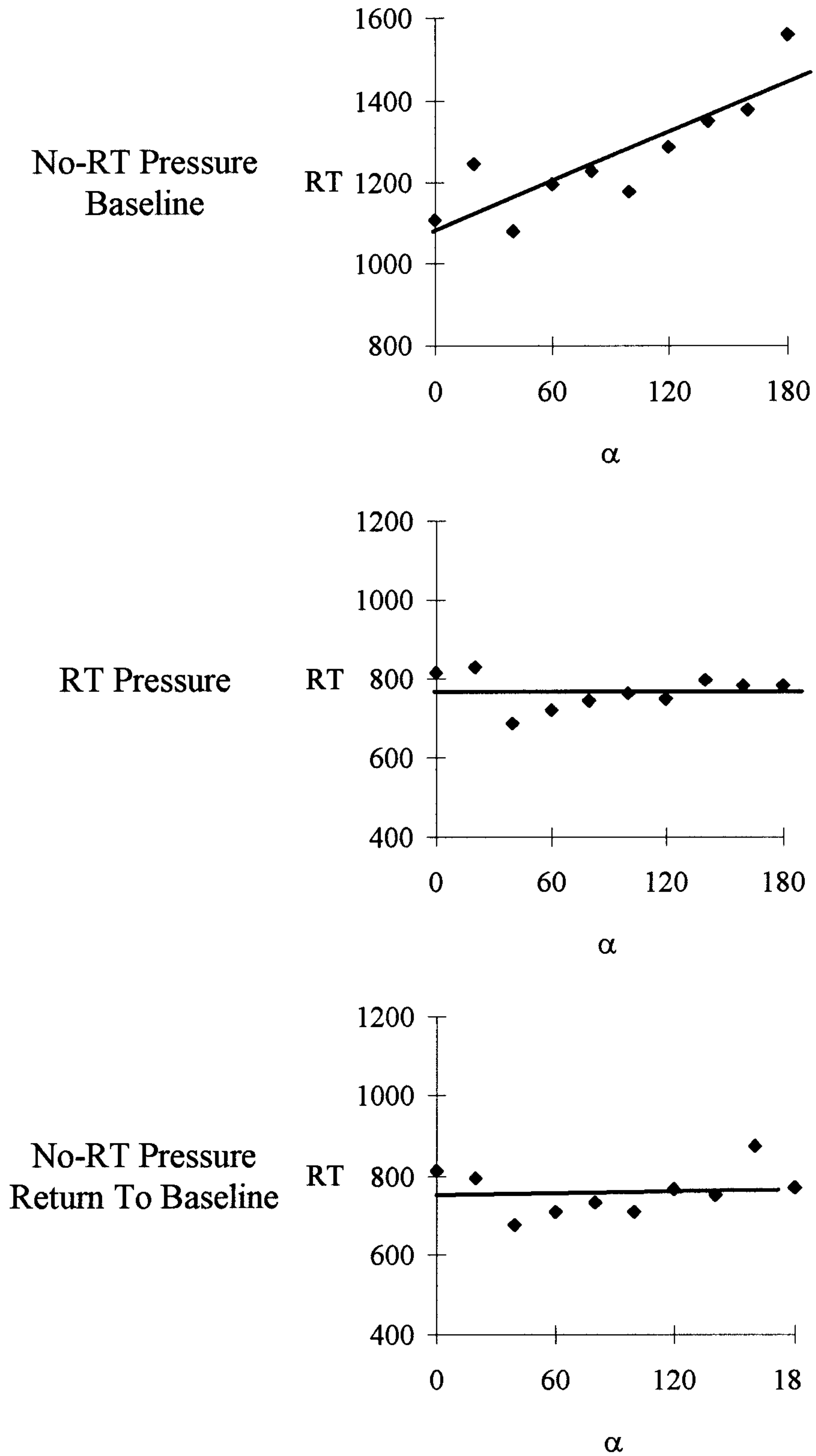


Fig. 4. Slope, intercept, and error data for Subject 3. See the caption of Figure 2 for details.


No-RT Pressure
Baseline
RT
1600
1400
1200
1000
800
0
60
120
180
α
RT Pressure
RT
1200
1000
800
600
400
0
60
120
180
α
No-RT Pressure
Return To Baseline
RT
1200
1000
800
600
400
0
60
120
18
α

revealing the plasticity of the speed of subjects' responses suggests that conclusions about fixed capabilities of individual performances should not be made based on data from experiments that exclusively use instructed contingencies. Instructed contingencies might not effectively motivate subjects to perform to their limits.

Interestingly, the manipulation was not reversible (the slopes of Subjects 1 and 2 did not return to their pre-RT pressure levels after the RT pressure was removed). All subjects' slopes, however, dramatically decreased in the first session of the RT pressure condition. This behavior is especially revealing when one considers the traditional durability of subjects' slopes in a handedness recognition task. The lack of reversibility when temporal contingencies are used is not a new finding. Baron and Menich (1985) and Baron et al. (1983) found that subjects' RTs did not increase once the temporal contingency was removed from a match-to-sample task. These findings demonstrate that temporal contingencies of this type have a relatively long-lasting effect. This finding is not well understood and deserves future attention.

For all subjects, error rates increased in the presence of the temporal contingency. For Subjects 1 and 2, this increase generally remained under 20% for all conditions. Such an increase in error rates is not uncommon when temporal contingencies are imposed. Baron and Menich (1985) and Baron et al. (1983) reported increases in error rates of about 20% when temporal contingencies were imposed in a match-to-sample task. When our temporal contingency was removed from Subject 1, his error rate decreased to that of the initial no-RT pressure condition, and his slopes remained at the level of the RT pressure condition. This finding indicates that the increased error rates found in the RT pressure condition are related more to the temporal contingency than to the subject's performance in the task. That is, the actual speed of the subject's response does not necessitate an increased error rate. It would be interesting to determine which aspect of the temporal contingency controls the error rates. For example, error rates may be influenced by the presentation of the beep, as opposed to the contingent relation, in the RT pressure condition. This hypothesis can be tested using a yoked control procedure.

There are limitations to our findings. Subject 3 could not complete the handedness recognition task in the RT pressure condition with a reasonable error rate (less than 20%). The failure of this subject to complete this task accurately needs to be explored. This failure, however, does not negate our results. All 3 subjects' slopes were effectively controlled by the temporal contingency. In addition, the error rates of Subjects 1 and 2 remained below 20%.

In conclusion, our data reveal that the slope of the function RT = $f(\alpha)$ can come under the control of temporal contingencies. One may conclude from this finding either that our subjects' speeds of rotation increased when temporal contingencies were administered or that these speeds were so fast that our subjects were not engaged in a mental rotation strategy. In either case, these findings indicate that the mental rotation strategy is not a fixed characteristic of the individual.

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Fig. 5. Mean RT data for all subjects plotted in 20° intervals. The top graph contains the data for the first no-RT pressure condition, the middle graph contains the data for the RT pressure condition, and the bottom graph contains the data for the second no-RT pressure condition.

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